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Introduction

For a number of years Russia, India and Brazil have outranked all other countries as producers of manganese ores. During the 5 years immediately preceding the European war, the average annual production of Russia was 844,000, of India 694,000 and of Brazil 200,000 long tons. Since the outbreak of the war there has been a considerable falling off in the Russian and Indian production, particularly in the former, whereas the production of Brazilian ores has been greatly increased, amounting in 1914 to over 250,000 tons and in 1915 to nearly 350,000, with conditions favorable for a still larger production in 1916. Manganese is one of the few industrially important metals that are not produced in the United States in quantity commensurate with our needs, so that we have been compelled to import annually about 300,000 tons, having a value of over $2,000,000, and these ores have been obtained from the three countries mentioned above. Their rank as contributors to our imports of manganese ores was India, Russia, Brazil; and in 1913, Brazil contributed only one-fifth. During the past 2 years Brazil has furnished rapidly increasing quantities to this country, and, with the falling off of imports from India and Russia, has become our principal foreign source. In 1914, Brazil furnished two-fifths of the imports and more than India or Russia, and in 1915 over nine-tenths. The manganese ores of Brazil are consequently of more than usual interest to us at this time.

The Manganese-Ore Districts of Brazil

The manganese mining industry of Brazil dates from the year 1894, and since that year the total production has been over 3,000,000 tons. With the exception of a small quantity produced in the State of Bahia from deposits west of the City of Bahia, this output has come from the

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State of Minas Geraes and has been exported through the port of Rio de Janeiro. In Minas Geraes there are two distinct, though not widely separated, manganese districts, known generally as the Miguel-Burnier and the Queluz or Lafayette districts. The Miguel-Burnier district was the first to be developed and for a number of years was the more important producer; but, since the phenomenal development of the Morro da Mina mine, the Lafayette district has assumed far greater importance.

In order to contrast the modes of occurrence of the deposits in the two districts, a brief description of the Miguel-Burnier district will be given, in the nature of a summary of a previously published fuller account.[1] The deposits of this district extend as a narrow belt about 10 miles long, parallel to the Ouro Preto branch of the Estrada da Ferra Central do Bresil, and lie at the southern edge of the great iron-ore region of central Minas Geraes. The orebodies occur as lenses or beds intercalated in a series of sedimentary strata showing a rapid succession of itabirite, schist, calcareous schist, and limestone. Stratigraphically they are found in the upper part of the Itabira iron-formation and in the lower part of the overlying Piraçicaba schist,[2] formations of probable Algonkian age. The ores are very high-grade manganese oxides, chiefly a mixture of psilomelane and pyrolusite, averaging 50 per cent. manganese, 1 per cent. silica, and 0.03 to 0.05 per cent. phosphorus. The great drawback of the district is the fact that the beds are steeply dipping and narrow, rarely over 6 ft. in width, so that expensive underground mining must be resorted to, and the individual deposits are relatively small. Two views have been advanced to explain the origin of the ores. H. K. Scott, who has written the most complete account of them, says:[3] "Whatever may have been the original state of the manganese ore bed, there can be no doubt that in its present condition, and down to the level to which it has been worked, it is a residual deposit from which the other elements have been leached out." O. A. Derby, in a discussion of Scott's paper, endorsed this view and referred to the original state of the manganese ore beds as limestone with varying proportions of metallic carbonates and siliceous impurities.[4] On the other hand, Harder and Chamberlin say:[5] "From their occurrence it must be assumed that they are similar in origin to the associated rocks, that is, that they are original sedimentary

[1] Joseph T. Singewald, Jr., and Benjamin LeRoy Miller: High-Grade Manganese Ores of Brazil. *The Iron Age*, vol. 97, pp. 417–420 (1916).

[2] E. C. Harder and R. T. Chamberlin: Geology of Central Minas Geraes, Brazil. *Journal of Geology*, vol. 23, pp. 358–363 (1915).

E. C. Harder: Manganese Ores of Russia, India, Brazil and Chile. *Bulletin* No. 113, p. 788 (May, 1916).

[3] H. K. Scott: Manganese Ores of Brazil. *Journal of the Iron and Steel Institute.* vol. 57, pp. 188–189 (1900).

[4] *Idem*, p. 212.

[5] *Op. cit.*, p. 406.

deposits of manganese oxide." The same statement is made by Harder alone.[6] Our own feeling is that while one cannot positively state that the ores were not laid down in the form of manganese oxides as integral parts of a sedimentary series, their relations to the associated limestones are such as to make their interpretation as residual products of decomposition and replacement of manganiferous limestone the more probable explanation of their origin.

The Lafayette District

Manganese deposits were discovered in the Lafayette district immediately after the inauguration of mining operations in the Miguel-Burnier district stimulated a search for manganese ores in Minas Geraes, but it was not until the year 1900 that the district became a regular producer, an output of 31,000 tons coming from the Piquery and São Gonçalo Mines in that year. This was increased to nearly 75,000 tons the following year, a production considerably in excess of that of the entire Miguel-Burnier district. In 1902, the Morro da Mina came in as a producer and firmly established the district as the chief manganese-producing district of Brazil.

Lafayette is a station, located at the edge of the town of Queluz, on the Estrada da Ferra Central do Bresil, about 32 km. south of Burnier and 462 km. from Rio de Janeiro. From the fact that the most important producing mines have been located in its vicinity the district has been generally referred to as the Lafayette district. The most important mine at present is the Morro da Mina, owned and operated by a Brazilian company known as the Companhia Morro da Mina, which has increased its production to 700 tons per day. It is located 7 km. northeast of Lafayette. On the same hill, a German company under the name Mineração de Agua Preta has been working the rubble ores to the east of the Morro da Mina ground. This company is producing at the rate of 2,000 tons per month and in the 6 or 7 years it has been operating has produced a total of 200,000 tons. On a small hill to the southeast of the Morro da Mina, the extension of that zone is being developed by a company known as the Companhia Queluz da Mina. The only other producing mine is the Cocuruto which lies about 40 km. southwest of Lafayette and is connected with the railroad at Christiano, a station 23 km. further south, by a 60-cm. gage line 40 km. in length. This mine has been operated about 7 years and is producing 3,000 tons monthly. It is owned by a Belgian company, the Société Anonyme de Manganese de Ouro Preto, which formerly worked the São Gonçalo Mine. After each had produced about 250,000 tons of ore, the São Gonçalo and Piquery mines were abandoned 10 years ago as worked out. They

[6] *Op. cit.*, p. 791.

were located about 15 km. northwest of Lafayette. The Piquery Mine is of particular interest in that it is the only one of which there is a geological description and it was there that Derby obtained the first evidence of the original character of the manganese rock from which the ores were derived.

In addition to those mentioned, a number of other deposits have been discovered and prospected to some extent, but apparently the results were not favorable enough to warrant further development as none of them became important producers. It is certain, however, that the district has not been thoroughly prospected and there is every reason to expect that systematic exploration would discover deposits equal to those that have been found.

Geology of the Lafayette District

The geology of the Lafayette district differs markedly from that of the Miguel-Burnier. It lies to the south of the area underlain by the

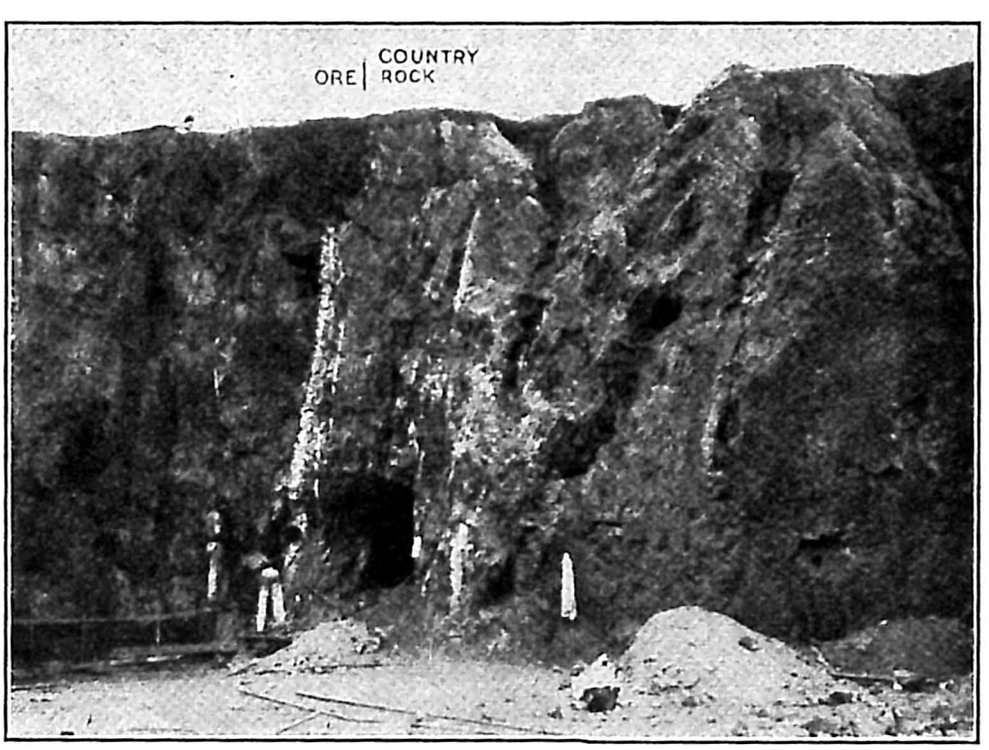

FIG. 1.—SHARP CONTACT OF MANGANESE ORE AND COUNTRY ROCK IN MORRO DA MINA MINE.

great iron-bearing series, and its ores are found in the basement complex of supposed Archean age which underlies a large part of the State of Minas Geraes. The rocks making up this basement complex are chiefly granite and gneiss with which are associated amphibolite, and micaceous and quartzose schists. There are also small intrusions of diorite and gabbro, mostly in the form of dikes. The granite seems to be intrusive into the gneiss and schist, but the relations between the schist and gneiss are not clear.

The manganese deposits occur as elongated masses of more or less lenticular shape within the rocks of the basement complex. As will be explained below, they represent residual products of decomposition of an original manganiferous rock made up of manganese carbonate and silicates. The immediate wall-rock of the deposits has likewise undergone decomposition, in many instances being nothing more than a clay in which the original rock texture is poorly preserved, so that it is usually difficult to determine its original character. In most cases, however, it seems to have been either gneiss or schist. The contact of wall-rock and ore generally appears quite sharp, as is shown in Fig. 1, but closer examination often reveals small nests and stringers of manganese oxide in the decomposed rock. There are also horses of equally decomposed rock and of the same character within the orebodies themselves.

The Piquery Mine

The geological relations of the Piquery orebody have been described by O. A. Derby in two papers published in 1901 and 1908,[7] and the following account is abstracted from them.

"The Piquery orebody presents the appearance of a mass of secondary material, or gossan, resulting from the alteration of a vertical dike or vein, some 10 or 12 m. wide. . . . The ore is a hard spongy black oxide, apparently consisting for the most part of psilomelane but with an admixture of other oxides that frequently occur in beautiful crystallizations in the spongy cavities. . . . In the midst of the merchantable ore occur inconstant bands and patches of hard siliceous material with the appearance of a quartzite, but which on examination proves to be composed almost exclusively of a finely granular mass of ashy white manganese garnet. A complete series of alteration phases between perfectly typical garnet rock and merchantable ore can be readily selected, and there can be no doubt that the latter results from the decay and leaching of the former."

Derby describes three phases of the garnet rock that he observed in 1901:

"1. A very fine-grained, compact and finely jointed rock of bluish-gray color with partings lined with asbestos. Under the microscope the rock is seen to be composed almost exclusively of closely appressed idiomorphic grains of white garnet showing a clear border but with the center highly charged with a fine black opaque powder that appears to be graphite. . . .

"2. A dark brown rock heavily charged with manganese oxide and too friable to permit the preparation of microscopic sections is evidently of the same type but more completely decomposed. . . .

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[7] O. A. Derby: On the Manganese-Ore Deposits of the Queluz (Lafayette) District Minas Geraes, Brazil. *American Journal of Science*, Ser. 4, vol. 12, pp. 18–32 (July, 1901).

O. A. Derby: On the Original Type of the Manganese-Ore Deposits of the Queluz District, Minas Geraes, Brazil. *American Journal of Science*, Ser. 4, vol. 25, pp. 213–216 (March, 1908).

"3. A milky white rock which under the microscope is seen to be composed of about equal parts of garnet and quartz. . . . The quartz in a fine mosaic about the garnet grains and in minute refilled joints is almost certainly secondary."

Residues of manganese garnet were likewise found by Derby at the São Gonçalo, Morro da Mina, Agua Limpa and Barroso Mines. The last two mines were located about 10 km. southeast and 9 km. south of Lafayette respectively. As the result of his observations at these mines, Derby drew the following conclusions concerning the origin of the deposits:

"The orebodies of the Queluz district are residual deposits derived through decomposition and leaching from an original type or types of rock in which manganese garnet was the most constant and characteristic silicate element. . . . This type, which may appropriately be denominated *queluzite*, is more or less intimately associated at São Gonçalo, Morro da Mina and Barroso with decomposed schistose rocks that evidently contained an original manganese-bearing silicate and which from the absence of recognizable clastic elements and from other characteristics, so far as they can be made out, is presumed to have been an amphibolic schist representing a sheared basic eruptive. . . . In the Agua Limpa schist, moreover, the manganese-bearing element is spessartine, as in the orebodies, thus giving greater plausibility to the hypothesis that the relation between these last and the above-mentioned rocks may be a genetic one. If thus related, the orebodies present strong analogies with those of magnetic titaniferous and chromic iron ores that are now generally considered as magmatic segregations in various types of eruptives, and, all things considered, this hypothesis seems the most plausible one for the manganese ores here discussed."

After the Piquery orebody was worked out and the original manganiferous rock was exposed in the bottom, Derby made a further study of it, the results of which are given in the 1908 paper. He found that the rock consists mainly of "a black, fine-grained, highly jointed and somewhat flaggy rock with the aspect of a limestone, with broad bands and patches of a more massive, yellowish-gray rock with the aspect of a quartzite." The latter is the garnet rock described in the previous paper, but which now turns out to be of secondary importance. The limestone-like rock on treatment with cold weak acid effervesces freely with an abundant separation of gelatinous silica and an insoluble residue containing spessartite and graphite. In places there is also a considerable admixture of rose-colored rhodonite in streaks and patches as the predominant component. Microscopic examination by Dr. Hussak showed the rocks to consist of manganese carbonate, tephroite, and spessartite with a small amount of rhodonite. The paper gives three analyses of these rocks, of which No. I was selected with reference to a supposed high carbonate content, No. II as having a lower carbonate content, and No. III was taken from the earlier paper and represents the garnet rock first found.

For the purpose of comparing the rocks represented by these analyses with the Morro da Mina rocks described below, their mineralogic composition has been calculated approximately on the basis of their described

Analyses of Original Manganese Rock at Piquery

	I	II	III
CO_2	22.62	4.59	.....
SiO_2	11.80	27.69	38.47
MnO	47.52	57.48	27.90
Al_2O_3	7.50	1.41	21.07
Fe_2O_3	.....	2.48	7.38
CaO	3.76	1.82	4.70
MgO	6.27	4.60	.....
	99.47	100.07	99.52

mineralogic characteristics. The commercial ores average twice as high in alumina as in ferric iron and on this basis there is just enough ferric iron and alumina in analysis I to take care of the silica in forming spessartite. If all the CO_2 is calculated as rhodochrosite, there is a deficiency of 4 per cent. MnO. But there is more than enough CaO and MgO to take care of this deficiency, so that roughly this rock consisted of 32.6 parts of spessartite and 59 parts of manganese carbonate by weight, or 32 and 68 parts respectively by volume. If in analysis II, the ferric oxide and alumina are calculated as manganese garnet, the CO_2 as rhodochrosite and the remaining silica as tephroite, there is a deficiency of nearly 9 per cent. MnO which is slightly more than covered by the CaO and MgO. On this basis the rock consisted of 12 parts of rhodochrosite, 14.5 parts of spessartite and 75.2 parts of tephroite by weight, or 17, 17.5 and 65.5 parts respectively by volume. Analysis III represents a garnet rock with a little more alumina and about 4 per cent. more silica than is needed to take care of the MnO, CaO, MgO and iron considered as ferrous iron. On this basis it consisted of 65 parts of spessartite, 12.6 of grossularite, and 15.3 of almandite by weight. Actually, of course, the rock consisted of a garnet intermediate in composition between the three but more nearly approaching the composition of spessartite. These calculations show the same great variation in the mineralogic composition of the Piquery rock that is found at the Morro da Mina Mine, except that rhodonite does not appear to have the prominence it attains at the latter.

These new observations necessitated different conclusions and Derby in this second paper says of the deposits that they "seem to be due to the alteration of an original rock with predominant carbonate of manganese and tephroite rather than of spessartite and rhodonite as hitherto supposed." In regard to the genesis of the rock he is silent in this paper, nor does he apply the term *queluzite* to it.

The Morro da Mina Mine

The Morro da Mina Mine is located on a hill 2 or 3 miles north of the town of Queluz, which has an elevation of 1,110 m. above sea level and rises to a height of 200 m. above the surrounding country. A branch

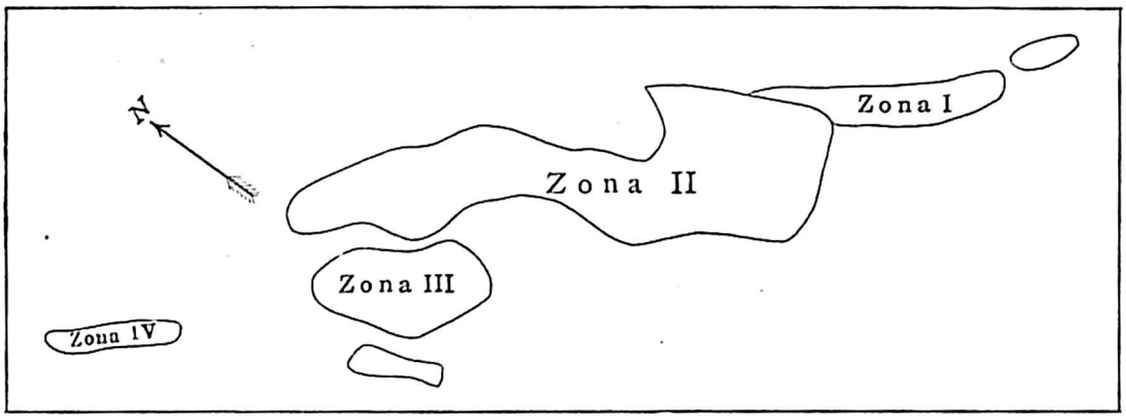

FIG. 2.—HORIZONTAL SECTION OF MORRO DA MINA OREBODIES AT LEVEL 55 M BELOW SUMMIT OF HILL.

line of the railroad connects the mine with the Estrada da Ferra Central do Bresil at Lafayette, so that the ore can be loaded into the cars at the

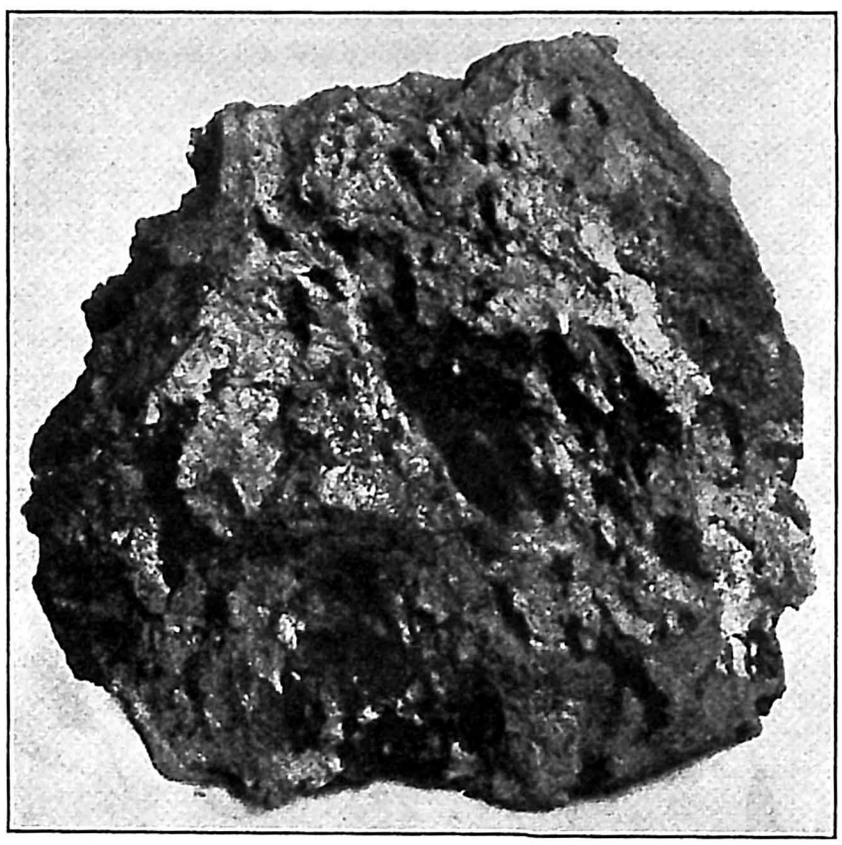

FIG. 3.—SOMEWHAT DRUSY MASSIVE PSILOMELANE, THE MOST COMMON TYPE OF ORE AT THE MORRO DA MINA MINE.

mine and requires no further handling until transferred to ships for exportation at Rio de Janeiro. The mine presents one of the most remarkable manganese deposits in the world both in respect to size and quality

of the ore; in fact, the manager of the mine, J. de A. Lustosa, says it is the largest known deposit of high-grade manganese ore. Since it became an important producer in 1902, it has yielded a total of over 1,000,000 tons, and in 1915 its production was about 200,000 tons. Development work has proved an ore reserve of 10,000,000 tons.

The orebodies occur at the top and on the flanks of the hill as a series of more or less overlapping lenses extending in a direction N 35° W., with a vertical dip and a pitch of 45° to the southeast. The relative positions, shapes and sizes of the orebodies that have been developed as they occur on the level 55 m. below the top of the hill are shown on the mine map in Fig. 2. The four largest are known as Zona I, II, III and IV respectively and have maximum dimensions of 200 by 30 m., 420

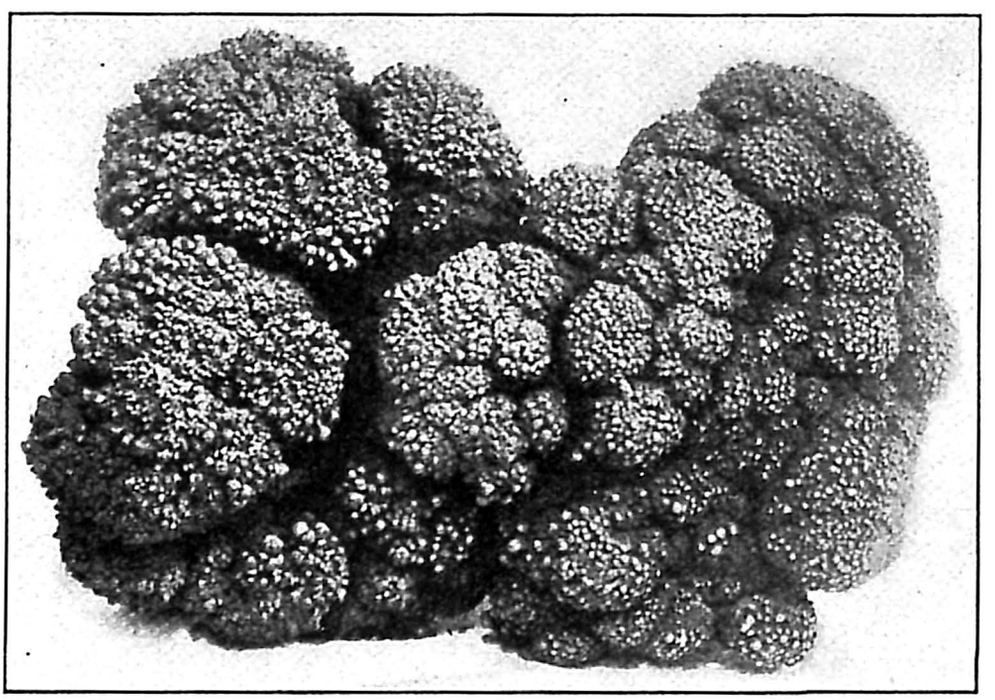

FIG. 4.—CAULIFLOWER-LIKE CLUSTER OF MANGANESE OXIDES FOUND QUITE FREQUENTLY IN THE MORRO DA MINA ORES.

by 120 m., 140 by 70 m., and 100 by 20 m. In depth Zona I and Zona II have been cut by a development tunnel 130 m. below the summit of the hill, indicating that the ores extend at least that far down. In addition to the ores *in situ*, a large part of the hillside below the ore outcrops is covered with rubble ore derived from them.

The ore consists for the most part of psilomelane, which occurs in a variety of forms. Most commonly it is simply more or less drusy massive psilomelane as in Fig. 3, but mammillary, botryoidal and concretionary forms are abundant and frequently quite elaborate. The surface of some of these, except for the black color, reminds one of cauliflower. A typical specimen is illustrated by Fig. 4. Associated with the psilomelane is considerable manganite and pyrolusite which occur for the most part as cavity linings and fillings in the former. The manganite occurs lining the cavities both in radiating groups of acicular crys-

tals and in distinct prismatic crystals. The pyrolusite is often pseudomorphic after manganite showing that it has in part been derived from it. The average composition of the ore as shipped is:

Average Analysis of Morro da Mina Ore

Water at 100° C	2.50 per cent.
Volatile	12.40 chiefly oxygen.
Insol. Residue	3.46
Fe_2O_3–Al_2O_3	8.75 alumina about twice ferric content.
Silica	1.76
P	0.069
S	Absent
Manganese	50.47

It is of interest to compare this average with the following mean of analyses of cargoes of manganese ores landed at Middlesborough, England, during the years 1897 to 1906 as compiled by L. L. Fermor[8] for samples dried at 100° C.:

	India	Russia
Mn	50.86	49.58
Iron	6.31	0.83
Silica	5.71	10.17
P	0.127	0.161
Alumina, etc	6.80	12.77

These figures indicate that the three countries produce very high-grade ore with the advantage in favor of the Brazilian ores, particularly over the Russian, as regards silica and phosphorus.

The ore is mined by hand for the most part in open cuts. A number of tunnels and adits have been driven, but these were intended either for development purposes or to connect the various open cuts to give access to the loading platforms and bins at the railroad. The method in vogue is to strip the orebody of such overburden as it may carry, and then as the ore is mined screen it over iron screens with 0.8-in. square openings. The oversize is the merchantable ore. The screenings constituting 15 per cent. of the crude ore, carry 34 to 35 per cent. Mn and are being stored apart from the waste to be beneficiated at some future time. The ore *in situ* furnishes two-thirds of the present output, and one-third is derived from workings in the rubble ores.

The Original Manganese Rock

Though decomposition of the original manganese rock has extended to considerable depth in places in the Morro da Mina Mine, to at least 130 m. as demonstrated in the exploratory tunnel previously mentioned,

[8] L. L. Fermor: Manganese-Ore Deposits of India. *Memoirs of the Geological Survey of India*, vol. 37, Pt. III, p. 518 (1909).

portions of the rock have escaped alteration and are well exposed in the mine workings. A large mass of the rock is actually exposed at the surface at the southwest corner of the outcrop of Zona II. It is characterized by a predominance of the silicates, and especially garnet, and for that reason has not succumbed to the processes of weathering. The abrupt transition from this rock to ore is shown in Fig. 5, and it is only the presence of numerous stringers, tongues and patches of manganese oxide penetrating the rock close to the ore that makes clear their genetic relations. More interesting and instructive exposures are found in the 130-m. tunnel. This tunnel crosscuts in a westerly direction the decomposed country rock for 120 m. to Zona I, then cuts diagonally across it in good ore for 150 m., and on emerging penetrates 50 m. of the manganese

FIG. 5.—SHARP CONTACT BETWEEN THE MANGANESE ORE AND THE ORIGINAL MANGANESE ROCK CHARACTERIZED BY AN ABUNDANCE OF MANGANESE GARNET.

rock to the ore of Zona II. After again cutting 50 m. of ore, a small horse of the manganese rock is encountered with ore on the opposite side. The four contacts of ore and rock exposed in this tunnel showed the same rapid change from one to the other with only a narrow transition zone marked by stringers and tongues of the black manganese oxide penetrating the manganese rock.

Most of this rock has the appearance of a fine-grained dark gray crystalline limestone and is easily scratched with the point of the pick. Its specific gravity, however, is considerably above that of limestone. Here and there are brown patches and streaks with a violet tinge that consist of massive garnet, and there are frequently spots and stringers of pink rhodonite that at once attract attention. A closer examination

reveals the presence of sufficient light pink silicate in much of the material to give a pinkish tone to its dominant gray color.

Examination of thin sections shows that the essential constituents are manganese carbonate, spessartite, rhodonite and tephroite. Taking the average of all the rock, the manganese carbonate is the most abundant mineral and the tephroite the least abundant. The spessartite is more widespread in its distribution but probably not much in excess of the rhodonite in actual quantity. The relative quantity of the different minerals varies most widely, so that some of the rock consists almost entirely of one of the minerals while some has them present in almost equal quantity, with the exception of the tephroite, which, in the sections examined, was never present in more than subordinate amount. In this respect the rock differs from the Piquery rock described by Derby in which tephroite was prominent and rhodonite a subordinate constituent. Which of the two minerals was formed in a given case depended undoubtedly on the relative amount of silica available, a low silica content giving rise to the formation of the orthosilicate tephroite and a higher silica content to the metasilicate rhodonite.

A thin section of a specimen most closely resembling crystalline limestone consists almost entirely of anhedral grains of manganese carbonate averaging between 0.16 and 0.25 mm. in diameter. That the carbonate is essentially manganese carbonate rather than calcium or magnesium carbonate is shown by the specific gravity of the rock, which is 3.55. The manganese carbonate is swarming with flakes of graphite ranging in size from 0.03 to 0.08 mm. and somewhat less abundantly with small garnets ranging from 0.01 to 0.03 mm. in diameter. In the entire slide there are only a few small areas containing rhodonite or tephroite. The minute garnets in this slide differ from the larger garnets in the more siliceous phases of the rock in being perfectly clear, whereas the latter are characterized by the presence of numerous minute black inclusions such as described by Derby as graphite in the rocks studied by him. Another specimen of more siliceous looking rock with a pinkish tone and streaks of rhodonite shows in thin section manganese carbonate, garnet, rhodonite and tephroite in abundance. The constituents average in size from 0.08 to 0.16 mm. with a few larger crystals of rhodonite. As is generally the case, the garnets are pronouncedly euhedral while the other minerals are anhedral. A specimen of particularly siliceous looking rock having a specific gravity of 3.8 consists for the most part of rhodonite with which is associated considerable euhedral garnet. The rock itself is light brown in color with a distinct pinkish tone. In addition to the silicates there is also an appreciable amount of the carbonate present. The garnets range in size from 0.10 to 0.15 mm. and the rhodonite crystals average about two or three times as large. Other thin sections show essentially similar features.

The manner in which this rock undergoes alteration to manganese oxides is very interesting. A specimen undergoing oxidation is illustrated

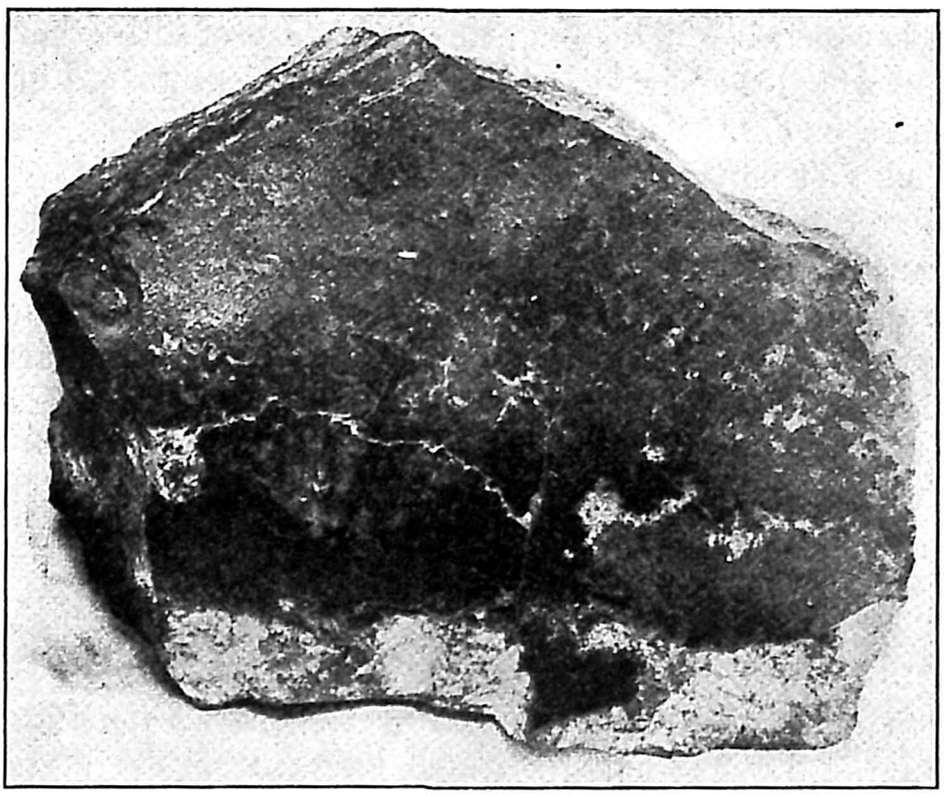

FIG. 6.—POLISHED SURFACE OF THE ORIGINAL MANGANESE ROCK IN PART ALTERED TO OXIDES OF MANGANESE. (Black areas and patches represent the manganese oxides.)

in Fig. 6. As the oxidizing solutions penetrate the rock they first break down the manganese carbonate, tephroite and rhodonite and leave

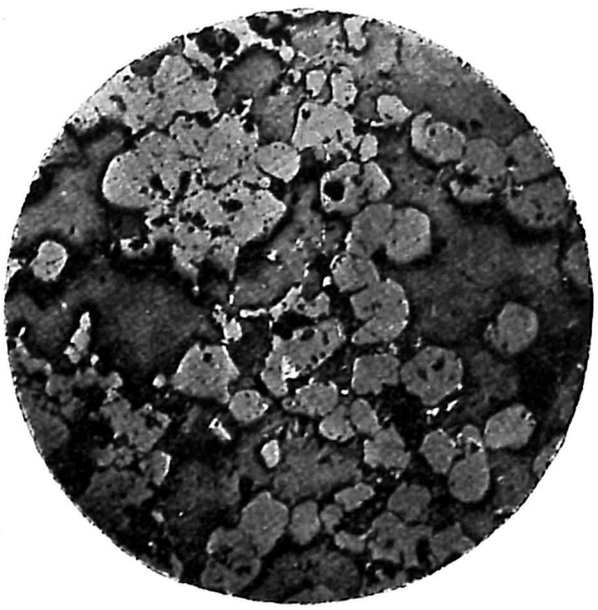

FIG. 7.—RESIDUAL GARNET GRAINS IN A GROUNDMASS OF MANGANESE ORE RESULTING FROM THE OXIDATION OF THE MANGANESE ROCK.

behind embedded in the manganese oxides the grains of garnet. That is, oxidation does not run ahead decomposing the manganese carbonate first

and then as a more advanced stage tephroite and rhodonite successively, as one might expect; but the three minerals are replaced simultaneously at the very front of the advance of oxidation. A magnified polished surface of rock which has undergone this first stage of alteration is shown in Fig. 7, in which the garnet crystals are seen disseminated in a matrix of manganese oxides. Such material from this mine was described by Derby in his first paper and both minerals considered primary elements of the rock. In his second paper he doubted this first interpretation and was more inclined to regard the manganese oxide a residue of the alteration of original carbonate and silicate minerals with retention of the spessartite. The evidence of the thin sections makes clear that the latter is the true explanation. As this material is further worked on by the oxidizing solutions, the garnet begins to succumb around the periphery of the grains and along fractures until finally it too has been replaced by the manganese oxides.

Genesis of the Lafayette Type of Deposit

The manganese deposits of the Lafayette district inevitably call to one's mind the Indian deposits which likewise consist of manganese oxides associated with manganese silicate rocks, and as we shall have occasion to refer to them in the discussion of their genesis, it will be helpful to summarize at the outset certain of the salient features of the Indian deposits as described by L. L. Fermor.[9] There are two main types of manganese deposits in India, associated respectively with the *kodurite* and *gondite* rocks. The former are found in the Vizagapatam district on the east coast, the latter in the Central Provinces and other parts of India. Typical kodurite is composed of potash feldspar, manganese garnet and apatite, with or without pyroxene. From the mineralogical and chemical composition of the rock and its geologic relations, Fermor concludes that kodurite is an igneous rock. It was subjected to alteration under oxidizing conditions and gave rise to the manganese ores. He finds that the manganese garnet is the most stable mineral and is often left behind in a matrix of psilomelane. To the gondite rocks he gives an entirely different interpretation. He thinks they were originally deposited as sediments and the manganese which they contain as chemical sediments, most probably in the form of oxide, though perhaps to a limited extent as carbonate. These sediments were later subjected to intense dynamo-metamorphism, and where they consisted of relatively pure chemical sediments of manganese were converted into compact psilomelane and braunite. Where alumina and silica had also been deposited, spessartite and rhodonite were formed, and if there was an excess of silica it was crystallized as quartz. The resultant rock is called

[9] *Op. cit.*

gondite. Typical gondite is a very fine-grained rock consisting of tiny round grains of spessartite set in a mosaic of quartz. Where alumina is deficient rhodonite is found. The ores associated with the gondite rocks, Fermor believes are the result of combined decomposition and replacement of them by waters containing CO_2 and O, but that this action took place at considerable depth and that the carbon dioxide was a portion of that liberated in the metamorphism of the rocks of the region and the oxygen a portion of that liberated in the conversion of the original manganiferous sediments into the manganese silicate rocks. A small proportion of softish and more or less porous ore he attributes to the later surficial alteration of the gondite.

An explanation of the genesis of the Lafayette manganese deposits involves two problems: First, the genesis of the original manganese rock; second, the alteration of it to manganese oxides, that is, to the manganese ores.

As the evidence is beyond question in regard to the second stage in the formation of these ores, that problem will be discussed first. The manner of occurrence of the orebodies, as for instance the change in depth of the Piquery ores into the manganese rock, the abundant evidence of the alteration near the surface of the manganese rock into ore and the microscopic evidence of the same phenomenon, point unmistakably to the derivation of the ores from the manganese rock under conditions of weathering in the zone of oxidation. That is, the ores were formed under conditions similar to those that gave rise to the ores of the kodurite rocks of India and not as Fermor thinks most of the ores in the gondite series were formed. The chemistry of the alteration of the Brazilian manganese rock is simple compared with that of the kodurite. The principal constituents to be removed are the CO_2 of the manganese carbonate and the SiO_2 of the silicates. Examples of the efficacy of meteoric waters for that purpose are so abundant and generally recognized that this part of the process hardly requires elaboration. The universal alteration of iron carbonates to oxides and hydroxides in the zone of oxidation and the enormous amount of silica removed from the iron silicates in the formation of the Lake Superior iron ores are illustrations of the same chemical actions on similar compounds of a chemically closely related element. In the kodurite rocks the removal of considerable alumina was also necessary and the chemistry of this was the only step that Fermor found at all difficult to explain. But even the very slight solubility of alumina in ordinary dilute meteoric waters he thought would suffice for its ultimate removal. This difficulty, however, hardly enters in our problem. Except in the case of the local phases of garnet rock, which has anyhow to a large extent resisted alteration, the alumina content of the original rock is no higher, and the few available analyses would indicate actually a little lower, than that of the ores; and, further-

more, the total amount involved in either is not over 5 per cent. Consequently the problem of the removal of alumina does not confront us.

The ores have been described as somewhat porous and drusy, but by no means to such an extent as would be called for if they merely represented the residual product of leaching of manganese carbonate and silicates. Nor is there evidence to indicate that their present more compact form is due to shrinkage in volume or compression of the residual manganese oxides; but the evidence both megascopic and microscopic shows that the decomposing solutions deposited manganese oxide, volume for volume for the silica and carbon dioxide removed. Meteoric waters encountering such large quantities of manganese carbonate cer-

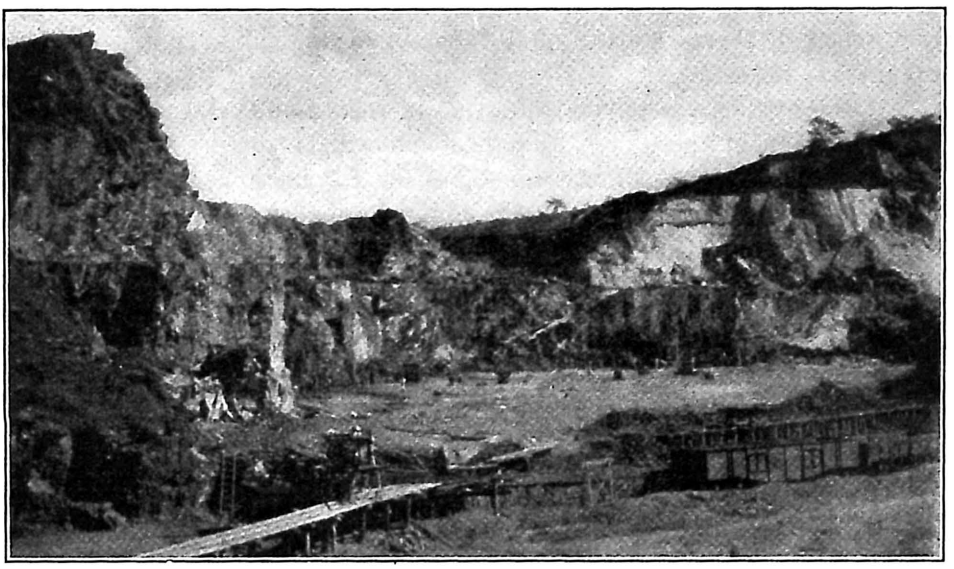

FIG. 8.—VIEW OF SOUTH END OF OPEN CUT OF THE MORRO DA MINA MINE, SAID TO BE THE LARGEST KNOWN DEPOSIT OF HIGH-GRADE MANGANESE ORE.

tainly took a great deal of it into solution as manganese bicarbonate which would be deposited at other points as the oxide; and in this way the deposition of manganese oxide accompanied the leaching of the other constituents of the rock. The alteration of the manganese rock to ore was, therefore, one of simultaneous leaching and addition, resulting in a relatively compact mass of the oxides. The present drusy character of some of the ore is clearly the result of subsequent action of solution and redeposition by meteoric waters upon the manganese oxides formed in this way.

The problem of the origin of the manganese rock is not so easy to solve. One is at once confronted with the fact that our knowledge is rather meager concerning the exact nature of the rocks with which it is associated

and its geologic relations to them, a full knowledge of which is essential to a final solution. The chemical, mineralogic and petrographic characters of the rock, however, do rule out some explanations, and point strongly to another. Further, the geologic relations that are reasonably well established are not at variance with this explanation but in a measure support it. That is, the sum of all evidence points to an analogy of this rock with the gondite of India. We believe that the rock is the product of dynamo-metamorphism of manganese sediments deposited in the form of manganese carbonate with varying but considerable quantities of silica and varying but smaller quantities of alumina. These sediments differed, therefore, initially from the gondite sediments in averaging much lower in silica, and by the deposition of the manganese in the form of carbonate instead of oxide; and this initial difference in composition accounts for the present difference in mineralogy of the two rocks.

The greater resistance to decomposition of the garnet in the manganese rock at the Piquery mine led Derby in 1901 to the erroneous conclusion that it consisted essentially of manganese garnet and to establish the rock type *queluzite* to which he attributed an igneous origin. Later, in 1908, he found that the garnet rock was but a subordinate phase of an entirely different type of rock which is essentially the same as that which we found abundantly at the Morro da Mina Mine. Attention has been called to the fact that in this later paper he does not apply the term queluzite to this rock and ventures no opinion as to its genesis. Though he did not specifically retract his earlier statement, the presumption is that, in the light of the discovery that the original rock was entirely different from what he had supposed, he abandoned his interpretation of its origin. In the meantime, L. L. Fermor,[10] on the basis of Derby's first paper, drew an analogy between this rock and his kodurite as regards their genesis, though calling attention to their dissimilarity in composition. A persistence of this same view is manifested in the statement by Harder and Chamberlin[11] in their discussion of these ores that "manganese ores associated with igneous rocks, such as those described above, occur abundantly in India—" and the statement by Harder[12] that "The relation of the manganese rock to the enclosing crystalline rocks has not been definitely determined; it may be interlayered with the gneiss or crystalline schist, or perhaps intrusive into them." The chemical and mineralogic composition of this rock as now established at both Piquery and Morro da Mina effectually precludes an igneous origin for it and demonstrates the presence of an original carbonate rock.

Even before Derby's second paper appeared, a view at variance with it

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[10] *Op. cit.*, pp. 273–274.
[11] *Loc. cit.*, p. 405.
[12] *Loc. cit.*, p. 790.

was expressed by his associate, E. Hussak.[13] He regarded the spessartite rock described by Derby together with a banded spessartite-rhodonite rock, which he mentions as occurring on the periphery of the Piquery orebody, the products of contact metamorphism by the eruptive gneiss of impure manganese carbonate sediments. The postulation of the derivation of the silicates from manganese carbonate in advance of the discovery of the presence of large amounts of carbonate is interesting. Beyschlag, Krusch and Vogt[14] are inclined to carry Hussak's ideas a step further and suggest that the manganese may have been contributed as part of the process of contact metamorphism. That this was not the case is proved by the fact that the carbonate still present, constituting a large percentage of the rock, is the manganese carbonate; and that consequently the original carbonate was a manganese carbonate. There remains to decide between the view of Hussak that the rock is the result of contact metamorphism of sedimentary beds of impure manganese carbonate and our own that it is a product of dynamo-metamorphism of such beds.

In the first place, the country rock of the ore deposits is not everywhere gneiss, but is in some cases schist, and these schists are admitted to be metamorphosed sediments. Nor are all of the gneisses necessarily igneous, though it has been generally held that they are such for the most part. Consequently the presumption is against assuming an igneous contact for all of the deposits. In the second place, the texture and appearance of the silicates is not that of typical skarn minerals, or products of contact metamorphism; but it is that of silicates crystallized in a carbonate rock that has been subjected to regional metamorphism. The reply might be made that the whole region has been subjected to dynamo-metamorphism subsequent to the contact metamorphism, but it is equally true that the texture of the rock is not what one would expect to result from a skarn rock subjected to regional metamorphism. On the other hand, we cannot escape the conclusion, demanded by both hypotheses, that there first existed impure manganese carbonate, and it is obvious that the rocks have undergone regional metamorphism. The inevitable result would be a rock such as we have. Our explanation is, therefore, in harmony with the available evidence and makes the manganese rock of the Lafayette district genetically identical with the gondite of India, the mineralogic difference of the two rocks being due to their initial difference in chemical composition.

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[13] Eugen Hussak: Ueber Atopit aus den Manganerzgruben von Miguel Burnier, Minas Geraes, Brasilien. *Centralblatt für Mineralogie, Geologie und Paläontologie*, 1905, pp. 240–245.

Eugen Hussak: Über die Manganerzlager Brasiliens. *Zeitschrift für praktische Geologie*, vol. 14, pp. 237–239 (1906).

[14] Beyschlag, Krusch, Vogt: *Die Lagerstätten der nutzbaren Mineralien und Gesteine*, vol. 2, p. 596, (1913).

Discussion

L. C. Graton, Cambridge, Mass.—I should like to ask the authors if they attempted to draw any analogies with the manganese deposits at Franklin Furnace, N. J., and whether there are any traces of zinc in these Brazilian deposits.

J. T. Singewald, Jr.—We did not think of them at all as analogous to the Franklin Furnace deposits and there is no appreciable percentage of zinc present. If these ores do contain zinc it could be there only as a fraction of a per cent.

F. Lynwood Garrison, Philadelphia, Pa. (communication to the Secretary*).—There is no disputing the fact that the manganese ore supply situation in this country demands serious consideration and is a matter of fundamental public concern. We are consuming this material at a steadily accelerating rate and there is no hope for a proportionate increase in the domestic supply.

In the year 1916, this country imported 560,000 tons and produced only 27,000 tons from our own territory In 1915, the local production was 9,709 tons, which on its face shows the American output to have tripled during the past year. Those of us who are familiar with the character and scope of the manganese deposits in this country, however, know perfectly well that these figures are deceptive and that no such ratio of increase can be expected and maintained. It therefore behooves us to give careful and immediate consideration to the sources of foreign supply now available to us, and at the present moment this means predominantly Brazil as long as the war endures.

As is well known, steel cannot be made in large quantities without the use of ferromanganese alloys, and in view of current political and economic events, it is plain that were our ports blockaded or our ships denied the freedom of the seas, the steel production of this country would necessarily be seriously affected if not practically paralyzed, for, unlike Germany before the war, it does not seem that we have accumulated any considerable reserve of manganese ores and, as I have indicated, our domestic yield last year was about 4½ per cent. of the consumption.

Prior to the war, we imported large quantities of ferromanganese from Europe. Inasmuch as both England and Germany have practically no domestic supply of manganese ores, like ourselves they had to depend upon importations chiefly from India and Russia. It is evident, therefore, that the situation in England and France is serious and in Germany must be desperate, for it is known that her reserves of manganese ore have long since been consumed and, failing the discovery of some suitable substitute as a deoxidizer in the process of steel manufacture, that

* Received Feb. 26 1917.

country today must be face to face with a problem of the utmost gravity in the consequently necessitated restriction of her steel production. Naturally we hear very little about the matter, for it is a technical subject beyond the ken of the general public in all countries. Most people assume that given an unlimited supply of iron ore and coal, a corresponding production of steel is simply a question of apparatus to make it.

The United States and Canada have been combed over pretty thoroughly in the hope of finding manganese deposits of sufficient magnitude to meet our needs, but so far with uniformly disappointing results. Plenty of manganiferous iron ore has been found in the Southern States and some superficial, but never rich, manganese ore deposits in residual clays. We have nothing in this country similar to the great deposits in Minas Geraes of the Lafayette type, although there is some resemblance between our Appalachian deposits in the Potsdam sandstone or quartzite and those of the Miguel-Burnier district which are also associated with quartzites. The latter, however, are infinitely larger, although they also are evidently superficial, but nevertheless by virtue of their size and extent must contain large bodies of good, merchantable ore.

Seemingly we have no cause to hope that there will ever be found in this country any manganese deposits comparable to those of India, Russia and Brazil. Since the war, the demand for Brazilian ore has increased in leaps and bounds, and were the handling and shipping facilities at Rio de Janeiro less archaic and primitive, the output might be greatly enlarged.

Rio de Janeiro is the only Brazilian port from which manganese ores are being shipped. About 9 or 10 years ago, attempts were made to mine and ship manganese ores from Bahia, and some small tonnage was exported, but the enterprise culminated in failure.

The existing productive districts of Brazil are today those and only those mentioned in the paper of Singewald and Miller and although quite distinct geologically they are very near together geographically. There is abundant reason to believe that the productive manganese area of this enormous country may be considerably enlarged as the result of well-directed and sustained exploration. But as yet little intelligent and systematic work of this kind has been attempted, although manganese ores have been discovered in numerous localities and the geologic data we already possess indicate the existence of many more yet to be found.

At present the Lafayette type of deposits appears to hold promise of larger ore reserves than those of the Miguel-Burnier class. From what is known of the genesis of the ores in both of these districts, it might seem that in neither case can much persistence in depth be expected of the orebodies. This would appear to be especially so with the deposits associated with and intercalated in sedimentary strata.

The genesis of the ores in the Lafayette district, as described by

Singewald and Miller, follows rather closely the hypothesis laid down by Derby some 20 years ago in which he called attention to the important role limestone and calcium compounds seemingly play in the origin of the Lafayette (Queluz) ores, as well as those in the sedimentary rocks.

The intimate relations between iron, manganese and limestone beds has long been recognized. The affinity of these two metals for certain quartzose rocks such as the itabirites of Brazil, the Potsdam sandstone of the Appalachian region and the quartzites of the Dharwar series in India, is equally noteworthy. But the suggestion made by Derby as quoted by the authors on page 12, to the effect that the orebodies of the Lafayette type present strong analogies to certain ore types in magmatic segregations, imports a new idea into the problem which it seems to me ought to receive careful consideration.

Before discussing this subject in detail, there are a few general facts connected with it which it might be well to review. Years ago Penrose pointed out that pre-Paleozoic rocks, especially the Archean, have played a far more important role as a source of manganese than the later igneous rocks.[1]

The sedimentary and residual ores of iron are fully paralleled by those of manganese, the gossan iron ores being the only ones having no true manganese equivalent.

The simultaneous leaching of iron and manganese from the rocks by the same solvents in much the same way is evident.

It is also plain that although these metals are redeposited under similar conditions, the precipitation takes place more or less separately. All manganese ores contain some iron, and most iron ores carry manganese, and it is important, as a practical matter, for us to understand, as far as it is possible, the chemical reactions involved in the question.

The carbonates of iron and manganese are isomorphous and are precipitated as such together. Resulting oxidation leaves the two metals associated in their relative proportions. The oxides of these metals, on the contrary, are not isomorphus and may be precipitated together only in mechanical association, as in bog ores. When iron and manganese ores occur in more or less separate deposits, different influences must have been at work from those that have thrown them down together.

According to Fresenius, the iron is precipitated first as ferric hydroxide, the manganese remaining in solution as a bicarbonate to be finally thrown down in a calcareous sinter, or, in other words, solutions of manganese carbonate are more stable than similar solutions of ferrous carbonate, and in consequence the manganese salt is carried or migrates farther, thus effecting at least a partial separation of the two metals from the same solution.

The thermo-chemical observations of Dieulafait are in accord with

[1] *Annual Report of the Arkansas Geological Survey* (1890), 544.

the above deductions and rest upon the principle that when several reactions may conceivably take place in the same solution, *the one attended by the greatest evolution of heat will occur.* The thermo-chemical equations of Dieulafait are important and in brief are as follows:

$$2FeO + O = Fe_2O_3 + 26.6 \text{ Cal.}$$
$$2MnO + 2O = 2MnO_2 + 21.4 \text{ Cal.}$$

If oxygen acts on a mixture of FeO and MnO, or upon substances equivalent to them, ferric oxide will form *first* and be the more stable.

$$FeO + CO_2 = FeCO_3 + 5.0 \text{ Cal.}$$
$$MnO + CO_2 = MnCO_3 + 6.8 \text{ Cal.}$$

When carbon dioxide unites with these oxides, then *the manganese compound will form first and be the more stable.* If oxygen and carbon dioxide act together in considerable excess, Fe_2O_3 and MnO_2 will both be formed; but if they act slowly in small quantities, the oxygen will go to produce Fe_2O_3, and $MnCO_3$ can be generated at the same time. Manganese carbonate, being somewhat soluble, may then be separated from the ferric oxide by leaching, either to be deposited as carbonate or perhaps to be later oxidized to MnO_2 and CO_2.[2]

Dieulafait gives the heat of formation of several manganese compounds as follows:

$$Mn + S = 22.6 \text{ Cal.}$$
$$Mn + O = 47.4 \text{ Cal.}$$
$$Mn + O + CO_2 = 54.2 \text{ Cal.}$$
$$Mn + O_2 = 58.1 \text{ Cal.}$$

Hence it appears that since the dioxide produces the most heat, it is also the most stable compound of the series and being the easiest formed becomes the principal manganese ore. Thus thermo-chemical and geological hypotheses are in harmony.

During a recent visit to Brazil, my attention was called to a manganese rock associated with granites and gneisses in a section not heretofore explored and many miles distant from the Lafayette district. On analysis this rock gave the following composition:

	Per Cent.
SiO_2	36.04
Al_2O_3	11.01
Fe_2O_3	9.90
MnO_2	37.00
Phosphorus	0.068

It will be noted that this material approximates closely in composition to that indicated in III, on page 13, and to typical spessartite which according to Rammelsberg contains 36.16 per cent. Al_2O_3 and 32.18 per cent. MnO.

[2] The Data of Geochemistry, *Bulletin of the U. S. Geological Survey* (1911), **491**, 511.

In the case of the ores of the Lafayette type, it is possible there may be reason to assume the manganese to be a replacement of silica rather than of lime. I have myself seen in other parts of Brazil large bodies of manganese ores associated with shales and quartzites similar to the Miguel-Burnier deposits, but no limestones, although, of course, future development may show their presence or that of calcareous shales.

In personally discussing this subject with J. C. Branner, whose work on Brazilian geology stands second only to that of Derby, he referred to an instance where he broke what seemed to be a solid lump of manganese and found that it was a fragment of itacolumite covered with a crust of psilomelane. Under the microscope a section of this core rock showed that the silica is being replaced by a brownish mineral of undetermined character which in turn was being replaced by solid psilomelane. Dr. Branner, therefore, concludes that: "in this case the ore is clearly a replacement of silica by manganese brought in in solution."

Now as to the magmatic segregation hypothesis suggested by Derby to account for the origin of certain Brazilian manganese ores: It may be recorded that a manganese rock similar to that whose analysis is given on page 13, has been found in the neighborhood of chromic iron-ore deposits in areas composed almost wholly of granites and gneiss, which are probably Archean.

Chrome ores are almost invariably found in serpentine rock and usually serpentines have been formed by the alteration of basic igneous rocks, chiefly pyroxenites and peridotites.

I have never heard of any chrome ores having been found in Minas Geraes, but serpentine seems to be a not uncommon rock in the manganese as well as in the iron districts.

Goodchild[3] in his paper on the subject of "Laterization in Minas Geraes" speaks of serpentine boulders occurring in the gorges between the canga flats to the south of Caraca having the following composition:

	Per Cent.
SiO_2	39.30
Fe_2O_3	9.36
Al_2O_3	5.94
Mn_3O_4	0.65
CaO	2.25
MgO	30.71

This rock corresponds rather closely to the typical peridotite derivatives given by Kemp in his *Handbook of Rocks*, page 140. Goodchild (page 15) refers to it as outcropping in the low country at the base of the Caraca mountain in the gorges between the canga flats.

Shearer[4] in the discussion of this paper of Goodchild, says of "the

[3] *Transactions of the Institution of Mining and Metallurgy* (1914), **23**, 14.
[4] *Ibid.*, 31.

serpentine rock found in the valleys on the Morro da Mina property southeast of the Serra do Caraca", the analysis of which is above quoted, that it "appears to be an altered basic lava flow overlying the iron formation and is the only late eruptive rock in the district and covers only a few square kilometers out of hundreds, so it cannot be supposed to have any genetic significance."

I am disposed to question this remark of Shearer's, for, on the contrary, I believe the existence of serpentines among the old rocks of central Brazil is an important matter. And in this connection I will venture to quote a remark upon the subject which Branner made in a recent letter to me. "A person well posted on the geology of Brazil sits up and takes notice whenever serpentine is mentioned, for it is supposed to have some genetic relation to the diamonds. I have only seen it in one place in Brazil, and if you know of occurrences, my suggestion is that you look it over carefully."

At the present time I am not at liberty to discuss this subject at length, save to say that I have myself found serpentines in several different localities in Brazil associated with granites and gneisses, and in every instance accompanied by minerals of economic importance.